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Measurements and modelling in complex terrain

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MEASUREMENTS AND MODELLING IN COMPLEX TERRAIN

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ABSTRACT: The main results of the EU-project "Measurements and Modelling in Complex Terrain" are presented. These include the preparation of the second volume of the European Wind Atlas – specifically directed towards wind resource assessment and siting issues in mountainous terrain – as well as the establishment of a comprehensive, CD-ROM-based database containing new, high-quality wind data from several topographically and climatologically complex regions of Europe. In the course of the project the limitations of the current Wind Atlas methodology has been identified and quantified, a novel concept of nested meso- and micro-scale models for wind resource assessment has been established, and a new model for the estimation of turbulence in complex terrain has been constructed.
Keywords: Wind Atlas, Mountains/High Terrain, Data Bases, Siting.

1 INTRODUCTION

The next volume of the European Wind Atlas – Volume II: Measurements and Modelling in Complex Terrain – is now being processed [9]. The new Atlas contains in condensed form the results of a comprehensive, multinational six-year EU-JOULE project with participants from 12 European countries.

The project itself has had four distinct tasks: 1) New wind measurements in mountainous terrain, 2) Meso-scale modelling, 3) Regional wind resource maps, and 4) Improvement of site-specific modelling. The work had several purposes: 1) To improve the knowledge of the European wind resources, 2) To improve the understanding of the existence and variability of the wind resources in mountainous terrain, 3) To improve the models for calculation of the wind resources and siting of wind farms in mountainous terrain, 4) To establish a database of the time-series of wind speeds and -directions measured during the project and a database of the turbulence data measured during experimental campaigns in Greece, France, Sweden and Denmark.

2 WIND MEASUREMENTS

Wind measurements have been carried out in Northern Portugal, in Galicia and the Ebro Valley in Spain, in Central Italy, in Ireland, on the Greek islands of Crete and Andros, in the Finnish Archipelago and Finnish Lapland, in Northern Sweden, and in Southern France. The measuring periods range from one to four years and the measuring heights from ten to thirty meters above ground level. Approximately 70 masts were operated.

The data are summarized for each station following an extended version of the layout in the European Wind Atlas [8]. An example of the new four-page station presentation is given in Fig. 1: Each station summary is printed on two pairs of facing pages. The first opening (upper panel) contains the station description, the station topography, the topographical model corrections employed, and several raw data summaries. The second opening (lower panel) provides the wind climatological fingerprint, the seasonal and inter-annual variation of wind speed, the calculated regional Weibull parameters, and the calculated regional mean wind speeds and energy densities.

All the raw data and derived statistics are furthermore collected in a database which will be made publicly available on a non-commercial basis.

2.1 Measurement recommendations

While a main purpose of the present project has been to provide wind data and wind atlas climatologies for several topographically complex regions of Europe – where the data coverage until now has been scarce or non-existent – much effort has also gone into securing the quality of the wind measurements. As atmospheric models and flow modelling becomes more sophisticated and accurate, the need for long-term, high-quality wind measurements becomes more and more apparent.

The accuracy of wind speed and direction measurements, as well as the applicability of these to wind energy studies, depend on a number of factors which were recently summarized by Mortensen [5]. These include:

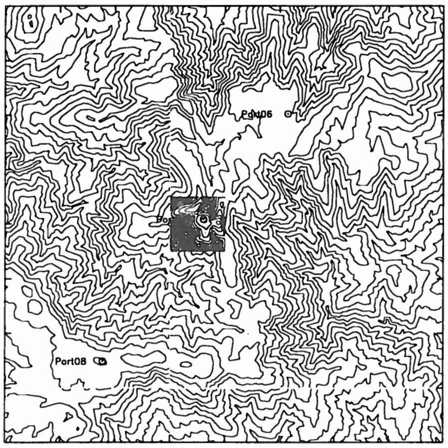
- Tower shadow and other effects
- Boom and clamp effects
- Anemometer design (ℓ_0)
- Turbulent biases for cup anemometers [4]:
  - Overspeeding: u-bias $\propto (\sigma_u/U)^2$
  - DP-error: v-bias $\propto (\sigma_v/U)^2$
  - Angular response: w-bias $\propto (\sigma_w/U)^2$
  - Stress-bias $\propto \langle uw \rangle/U^2$
- Calibration procedures:
  - Wind tunnel studies
  - Atmospheric (in situ)
- Anemometer maintenance
- Siting of anemometers
- Documentation of wind measurements and measurement conditions

Careful attention to each of these factors and comprehensive documentation of the measurement conditions are prerequisites to obtaining high-quality wind data suitable for wind energy applications and/or testing of models. Given the importance of this, a series of measurements recommendations have been worked out during the project and included in the Atlas.

Station 07 (Drave)		**Portugal**
40° 51′ 17″ N 08° 06′ 11″ W	E 575 598 m N 4 523 085 m	982 m

The mast is situated in the southern part of the Serra de S. Macário mountains, about 1.5 km SE of the village of Drave. The surface consists of low scrub. Going E and SE from the mast trees become more abundant and from a distance of 4-5 km the surface is covered by coniferous forest. There are no houses or other obstacles close to the mast.

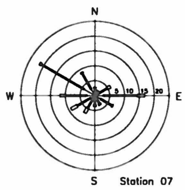
On the map below, the height contour interval is 50 m and 10 m, respectively, and tick marks are shown for every kilometer.

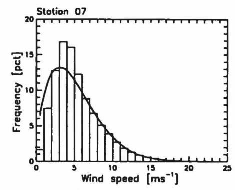


Sector	Input		Obstacles		Roughness		Orography		z_{0m}
0	0.0	0.0	0.0	0.0	0.0	0.0	61.5	1.6	0.0300
30	0.0	0.0	0.0	0.0	0.0	0.0	75.8	6.1	0.0300
60	0.0	0.0	0.0	0.0	0.0	0.0	95.3	4.4	0.0300
90	0.0	0.0	0.0	0.0	0.0	0.0	101.4	−1.3	0.0300
120	0.0	0.0	0.0	0.0	0.0	0.0	87.3	−5.9	0.0300
150	0.0	0.0	0.0	0.0	0.0	0.0	67.9	−4.9	0.0300
180	0.0	0.0	0.0	0.0	0.0	0.0	61.5	1.6	0.0300
210	0.0	0.0	0.0	0.0	0.0	0.0	75.8	6.1	0.0300
240	0.0	0.0	0.0	0.0	0.0	0.0	95.3	4.4	0.0300
270	0.0	0.0	0.0	0.0	0.0	0.0	101.4	−1.3	0.0300
300	0.0	0.0	0.0	0.0	0.0	0.0	87.3	−5.9	0.0300
330	0.0	0.0	0.0	0.0	0.0	0.0	67.9	−4.9	0.0300

Height of anemometer: 10.0 m a.g.l. 199106301535 - 199502161005

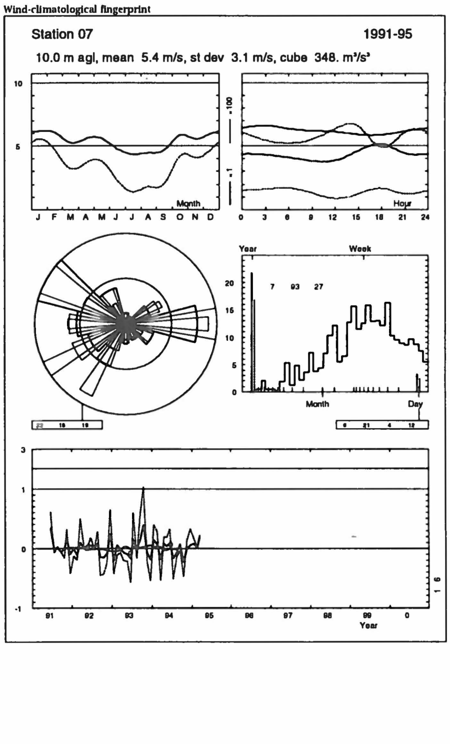
Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	*A*	*k*
0	2.7	49	171	200	161	123	97	70	47	29	37	12	4	1	0	4.4	1.52
30	1.9	71	230	195	155	106	74	51	35	26	32	17	7	2	1	3.9	1.28
60	6.0	20	70	78	86	107	117	115	114	88	125	53	18	6	2	7.3	2.23
90	16.8	9	51	107	135	140	134	107	92	77	99	38	8	2	0	6.5	2.07
120	7.0	21	114	174	168	148	122	85	60	43	46	15	4	0	0	5.1	1.79
150	3.6	32	112	141	137	123	115	94	66	48	74	36	21	2	0	5.8	1.68
180	3.7	30	86	109	128	129	110	95	77	63	103	47	20	4	0	6.4	1.82
210	6.7	17	64	82	101	113	97	81	71	65	109	82	58	35	25	8.0	1.68
240	9.2	17	69	93	125	116	92	88	77	66	101	65	45	24	21	7.4	1.63
270	11.8	16	73	132	190	173	116	76	61	47	56	29	16	8	6	5.4	1.46
300	21.5	7	49	137	242	237	149	80	43	23	21	7	2	1	0	5.0	2.10
330	9.0	14	84	168	208	174	123	85	59	38	31	11	3	2	0	5.0	1.83
Total	100.0	16	74	127	168	160	122	88	67	51	66	32	15	7	4	5.7	1.59





	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	6.4	6.4	5.2	5.5	5.3	4.6	4.4	4.1	4.4	5.8	5.6	5.9	5.3
1	6.4	6.3	5.4	5.6	5.5	4.9	4.4	4.4	4.4	6.0	5.6	6.1	5.4
2	6.5	6.2	5.5	5.5	5.5	4.9	4.4	4.3	4.4	6.1	5.7	6.0	5.4
3	6.6	5.9	5.6	5.5	5.7	4.7	4.3	4.3	4.7	6.2	5.8	6.2	5.5
4	6.5	5.9	5.5	5.6	5.5	4.8	4.3	4.5	4.9	6.1	6.0	6.3	5.5
5	6.5	6.0	5.3	5.7	5.3	5.1	4.2	4.4	4.9	6.0	5.8	6.1	5.4
6	6.4	6.1	5.2	5.8	5.4	5.0	4.1	4.5	4.8	6.1	5.7	6.3	5.4
7	6.4	6.2	5.3	5.5	5.3	4.9	4.1	4.5	4.8	6.0	5.5	6.1	5.4
8	6.2	5.9	5.2	5.6	5.5	5.1	4.0	4.4	4.7	5.6	5.6	6.3	5.3
9	6.2	6.1	5.2	5.5	5.5	4.9	3.8	4.3	4.4	5.7	5.6	6.1	5.3
10	6.1	6.3	5.1	5.3	5.8	4.6	3.7	4.0	4.3	5.8	5.2	6.0	5.2
11	6.2	6.1	5.1	5.3	5.8	4.5	3.8	4.2	4.5	6.0	5.3	5.9	5.2
12	6.1	6.5	5.0	5.6	6.0	4.5	3.9	4.1	4.5	5.9	5.4	5.9	5.3
13	6.0	6.1	5.0	5.7	6.3	4.5	4.2	4.4	4.7	5.6	5.3	5.9	5.3
14	5.9	6.0	5.1	5.8	6.1	4.8	4.4	4.5	4.9	5.8	5.5	5.8	5.4
15	5.9	5.9	5.1	5.9	6.0	4.8	4.6	4.9	4.9	5.9	5.4	5.8	5.4
16	5.9	5.8	5.1	5.8	5.9	4.7	4.8	5.1	4.9	5.5	5.2	5.6	5.4
17	5.5	5.8	5.3	5.9	5.7	4.9	5.0	5.1	5.0	5.8	5.4	5.7	5.4
18	5.9	5.8	5.4	5.8	5.8	5.0	5.2	5.1	5.1	5.8	5.4	5.8	5.5
19	5.9	5.8	5.4	5.9	5.6	5.0	5.0	5.1	5.1	5.7	5.5	5.9	5.5
20	5.9	6.1	5.5	5.6	5.4	4.8	4.8	4.6	4.8	5.8	5.7	6.0	5.4
21	6.2	6.1	5.2	5.4	5.0	4.7	4.4	4.3	4.6	5.8	5.6	6.0	5.3
22	6.3	6.2	5.4	5.4	5.1	4.7	4.2	4.2	4.5	5.9	5.6	6.1	5.3
23	6.4	6.2	5.4	5.3	5.3	4.6	4.4	4.1	4.3	5.9	5.7	6.1	5.3
Mean	6.2	6.1	5.3	5.6	5.6	4.8	4.4	4.5	4.7	5.9	5.5	6.0	5.4

Wind-climatological fingerprint



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1991						6.4	4.4	4.5	4.4	5.8	6.5	5.4	—
1992	6.1	5.4	5.8	5.6	5.9	5.1	4.4	4.8	4.0	5.0	5.0	7.4	5.4
1993	4.9	6.4	5.2	5.2	5.1	4.0	5.0	4.4	5.3	8.2	5.1	4.9	5.3
1994	7.0	6.4	4.3	6.1	5.9	5.2	3.6	4.1	5.0	4.6	5.6	6.3	5.3
1995	6.7	6.1	6.3	—	—	—	—	—	—	—	—	—	—
Mean	6.2	6.1	5.3	5.6	5.6	4.8	4.4	4.5	4.7	5.9	5.5	6.0	5.4

Roughness Class 0 (z_0 = 0.0002 m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	4.1	4.2	5.1	4.7	4.3	4.5	5.6	6.4	5.6	4.2	3.9	4.1	4.6
	2.08	1.82	2.49	2.49	2.28	1.99	1.98	1.99	1.90	1.74	2.24	2.27	1.92
25	4.5	4.6	5.6	5.1	4.7	4.9	6.2	7.0	6.1	4.7	4.2	4.5	5.0
	2.15	1.87	2.58	2.56	2.36	2.06	2.05	2.05	1.96	1.79	2.31	2.34	1.98
50	4.9	5.0	6.0	5.5	5.1	5.3	6.6	7.5	6.6	5.0	4.5	4.8	5.4
	2.20	1.92	2.64	2.63	2.42	2.11	2.10	2.11	2.01	1.83	2.37	2.40	2.03
100	5.3	5.4	6.6	6.0	5.5	5.8	7.2	8.1	7.2	5.4	4.9	5.2	5.9
	2.13	1.86	2.56	2.55	2.34	2.05	2.03	2.04	1.95	1.78	2.30	2.33	1.97
200	5.8	5.9	7.3	6.6	6.1	6.4	7.9	9.0	7.9	6.0	5.4	5.8	6.5
	2.02	1.76	2.42	2.41	2.22	1.94	1.92	1.93	1.85	1.69	2.18	2.20	1.87
Freq.	5.9	3.0	5.0	11.8	9.3	5.5	4.8	6.8	8.0	9.3	16.5	14.1	100.0

Roughness Class 1 (z_0 = 0.0300 m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.8	3.0	3.7	3.2	2.9	3.3	4.1	4.4	3.7	2.8	2.7	3.0	3.2
	1.60	1.54	2.17	2.06	1.85	1.67	1.72	1.64	1.59	1.52	2.06	1.91	1.66
25	3.4	3.6	4.4	3.9	3.5	4.0	4.9	5.3	4.5	3.4	3.3	3.6	3.9
	1.73	1.66	2.35	2.22	1.99	1.79	1.86	1.77	1.72	1.65	2.22	2.06	1.78
50	4.0	4.2	5.1	4.4	4.1	4.6	5.7	6.2	5.2	3.9	3.8	4.2	4.5
	1.94	1.87	2.64	2.50	2.24	2.02	2.09	1.99	1.93	1.85	2.50	2.31	1.97
100	4.7	5.1	6.0	5.3	4.8	5.5	6.8	7.3	6.2	4.7	4.5	4.9	5.3
	2.06	1.99	2.81	2.67	2.38	2.15	2.22	2.12	2.05	1.97	2.67	2.46	2.09
200	5.9	6.3	7.5	6.6	6.0	6.8	8.5	9.1	7.7	5.8	5.6	6.1	6.6
	1.97	1.90	2.69	2.55	2.28	2.05	2.12	2.03	1.96	1.88	2.55	2.35	2.01
Freq.	3.5	2.8	5.9	13.8	7.7	4.7	4.8	7.5	8.2	9.8	18.9	12.4	100.0

Roughness Class 2 (z_0 = 0.1000 m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.5	2.8	3.1	2.8	2.6	3.0	3.6	3.8	3.1	2.5	2.4	2.7	2.8
	1.58	1.65	2.14	2.10	1.85	1.67	1.71	1.65	1.56	1.58	2.03	1.97	1.67
25	3.1	3.4	3.8	3.5	3.2	3.7	4.5	4.7	3.9	3.0	3.0	3.3	3.5
	1.69	1.76	2.29	2.25	1.98	1.79	1.83	1.76	1.67	1.69	2.17	2.10	1.78
50	3.6	4.0	4.5	4.1	3.8	4.3	5.3	5.6	4.6	3.6	3.5	3.8	4.1
	1.87	1.95	2.53	2.49	2.19	1.98	2.02	1.95	1.84	1.87	2.40	2.33	1.96
100	4.3	4.8	5.3	4.9	4.5	5.2	6.3	6.7	5.5	4.3	4.1	4.6	4.9
	2.05	2.14	2.79	2.74	2.40	2.18	2.22	2.14	2.02	2.05	2.64	2.56	2.13
200	5.3	5.9	6.6	6.0	5.5	6.4	7.8	8.2	6.7	5.3	5.1	5.7	6.0
	1.97	2.05	2.67	2.62	2.30	2.08	2.13	2.05	1.94	1.97	2.53	2.45	2.04
Freq.	3.4	3.1	6.7	13.2	7.4	4.7	5.1	7.6	8.4	10.7	18.2	11.6	100.0

Roughness Class 3 (z_0 = 0.4000 m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.0	2.3	2.4	2.2	2.1	2.4	2.9	2.9	2.4	1.9	1.9	2.1	2.2
	1.59	1.74	2.07	1.99	1.79	1.68	1.72	1.64	1.52	1.64	1.96	1.84	1.65
25	2.6	3.0	3.1	2.9	2.7	3.2	3.8	3.9	3.1	2.5	2.5	2.7	2.9
	1.68	1.84	2.20	2.11	1.90	1.78	1.82	1.74	1.61	1.74	2.08	1.95	1.75
50	3.2	3.6	3.8	3.5	3.3	3.9	4.6	4.7	3.8	3.1	3.0	3.3	3.5
	1.83	2.00	2.39	2.30	2.06	1.94	1.98	1.89	1.74	1.88	2.26	2.12	1.88
100	3.9	4.3	4.5	4.2	4.0	4.7	5.6	5.7	4.6	3.7	3.7	4.0	4.3
	2.08	2.28	2.72	2.62	2.35	2.20	2.25	2.15	1.98	2.15	2.57	2.41	2.12
200	4.7	5.3	5.6	5.2	4.9	5.7	6.8	7.0	5.6	4.5	4.5	4.8	5.2
	2.00	2.20	2.62	2.52	2.27	2.12	2.17	2.08	1.91	2.07	2.48	2.33	2.05
Freq.	3.3	3.5	7.8	12.4	6.9	4.7	5.4	7.7	8.7	12.0	17.2	10.4	100.0

z	Class 0		Class 1		Class 2		Class 3	
m	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
10	4.1	82	2.9	34	2.5	22	2.0	11
25	4.5	104	3.4	53	3.1	39	2.6	23
50	4.8	126	4.0	74	3.6	57	3.1	38
100	5.2	165	4.7	117	4.3	90	3.8	60
200	5.7	236	5.9	235	5.4	176	4.6	113

Figure 1: Sample four-page station statistics summary (ie two openings) for the Portuguese station Drave [9].

3 MODELLING

An important objective of the measuring campaigns has been to provide wind data which are adequate for the improvement of models for site-specific calculations and for the construction of a model system for regional wind resource assessments. Four regions in four countries with different complex topography and climatic conditions were selected for the measuring campaigns. The regions are depicted in Fig. 2.

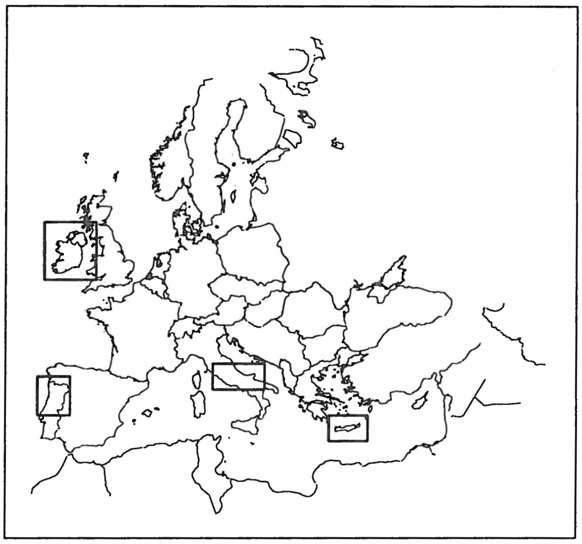


Figure 2: The four regions selected for intensive measurement and modelling campaigns.

The modelling work has thus concentrated on three main themes: 1) Investigating the accuracy and limitations of current wind resource assessment and siting tools – thereby providing data and information for the improvement of these models, 2) Implementing a new concept of nested models for regional wind resource assessment, and 3) Constructing a new model to estimate the turbulent wind conditions in complex terrain.

3.1 Limitations of WA^{S}P

The model used for the European Wind Atlas [8] has a number of characteristics which limits its straightforward use to certain atmospheric and/or topographical conditions:

- Prevailing conditions must be near-neutral
- Orography must be gentle (attached flow)
- Meso-scale effects are not accounted for.

The influence of atmospheric stability has been investigated both over land and offshore – examples of the results obtained are given in this volume by Barthelmie et al. [1] and Mortensen and Said [7].

Also in this volume is a report on the achievement on the purpose of improving micro-siting models given by Bowen and Mortensen: Exploring the Limits of WA^{S}P – the Wind Analysis and Application Program [2, 6]. It has especially been attempted to understand the magnitude and variability of the wind resource in mountainous terrain and to quantify the limitations of current micro-siting models in such terrain. Most importantly, a simple indicator of the complexity of a given terrain has been established, which provides some insight into the accuracy of WA^{S}P predictions in mountainous terrain.

3.2 Nested models for resource assessment

The meso-scale effects not accounted for by the current Wind Atlas methodology have been addressed by nesting meso- and micro-scale models in the calculation of the regional wind resources of a region. These results are reported in detail elsewhere in this volume by Frank and Landberg: Modelling the Wind Climate over Ireland [3].

3.3 Turbulence in complex terrain

Finally, the WA^{S}P model [6] has been extended by a module which can predict the turbulence component spectra of (u, v, w) over moderately complex terrain as depicted in Fig. 3. The model builds on the the rapid distortion theory.

4 CONCLUSIONS

The EU-project *Measurements and Modelling in Complex Terrain* (JOUR/0067) has contributed substantially to our knowledge of the European wind resources and to our understanding of the variability and magnitude of these wind resources in mountainous terrain. Concurrently, the models for calculation of wind resources and siting in mountainous terrain have been improved. Specific results and outputs of the project are:

- A database on a CD-ROM containing new high-quality wind data from several complex regions of Europe, ie mean wind speed data, turbulence data, and wind atlas data sets.
- A second volume of the European Wind Atlas [9].
- The limitations of WA^{S}P quantified [2].
- Improved model for siting (WA^{S}P), including a model for turbulence over complex terrain.
- New and improved wind atlas data sets for some mountainous regions of Europe and a model-complex for producing such data: the Karlsruhe Atmospheric Mesoscale Model + WA^{S}P.

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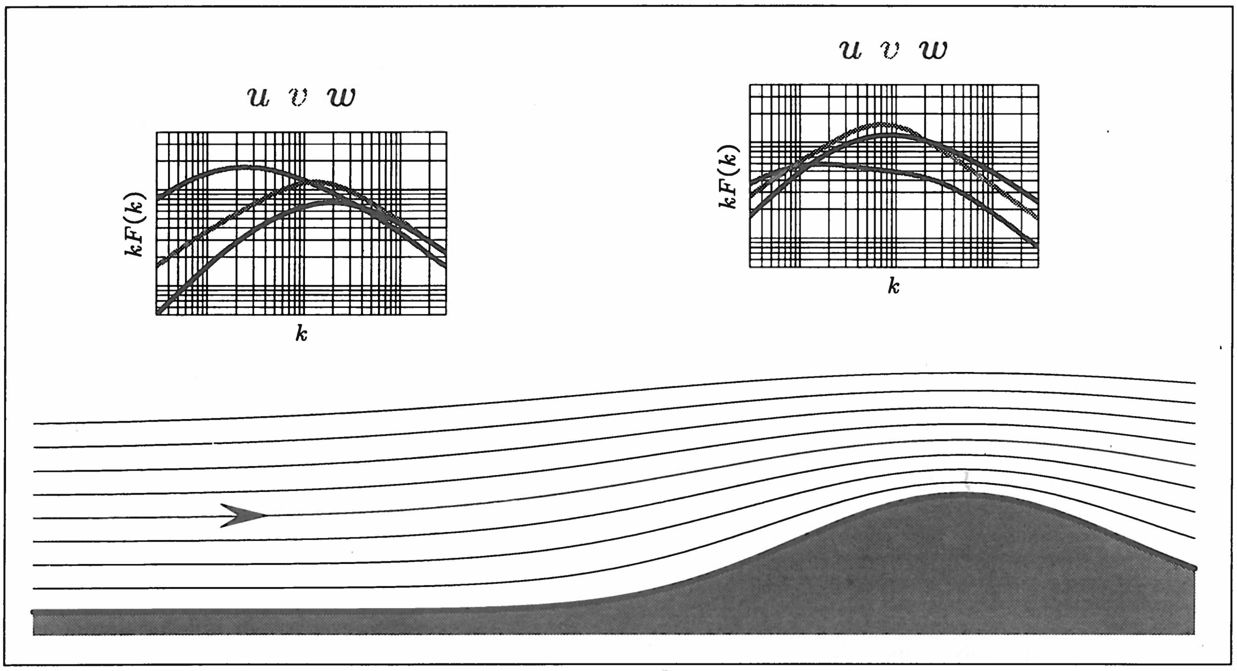

Figure 3: Sketch of wind flow over a hill. The change in the spectra of turbulence can be estimated using rapid distortion theory.

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